3D Reconstruction of Stents and Guidewires in an Anthropomorphic Phantom From Three X-Ray Projections

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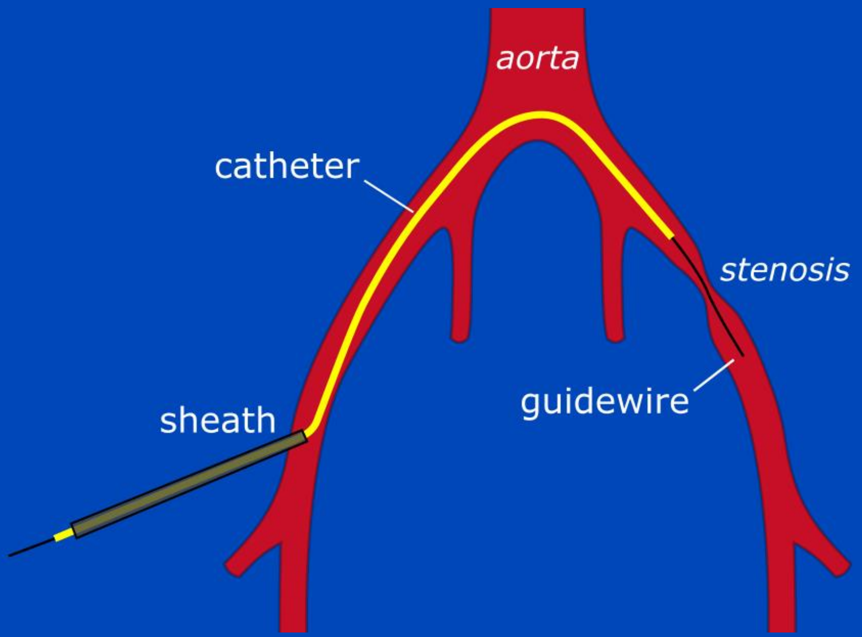
Interventional Radiology

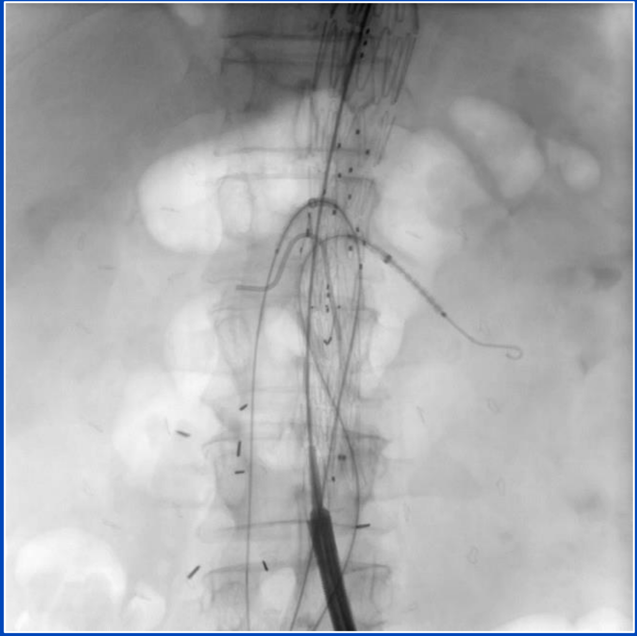
- Minimally invasive diagnosis or treatment, e.g. tumor embolization, treatment of aneursyms or stenoses, …
- Tools, e.g. guidewires, catheters, stents, get introduced into the patient through small incisions
- Intervention is performed percutaneously
- Requires image guidance



2D vs. 3D Fluoroscopy

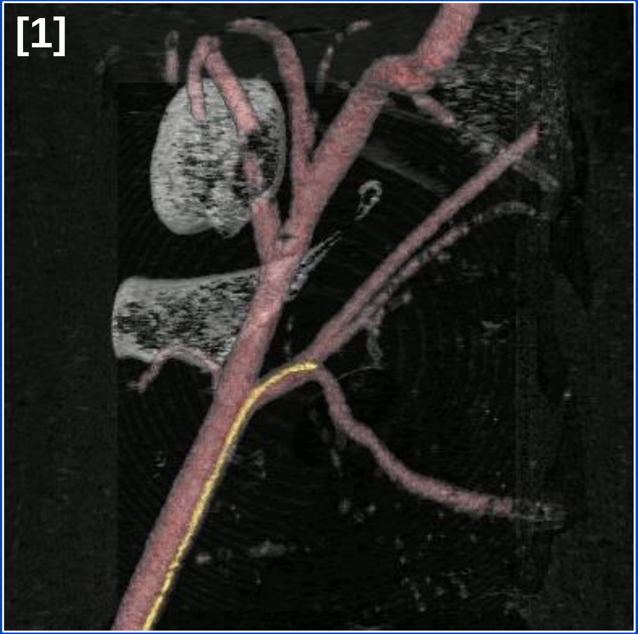
X-Ray-Based 2D Fluoroscopy

- Commonly used today
- Sequence of 2D x-ray images is displayed
- High spatial and temporal resolution
- No depth information



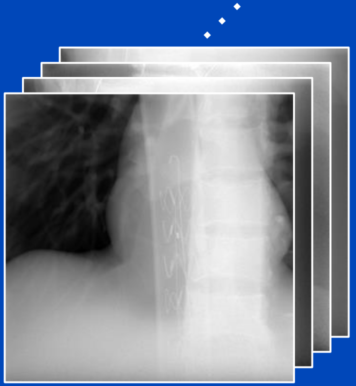
X-Ray-Based 3D Fluoroscopy [1]

- Sequence of 3D images, reconstructed from 2D x-ray images
- Full 3D information
- Only very few x-ray projections can be acquired per 3D reconstruction to limit dose



[1] Kuntz, Kachelrieß, Bartling *et al.*, *Eur. Radiol.* Vol. 23, pp. 1669–1677, 2013.

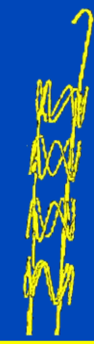
3D Fluoroscopy Pipeline



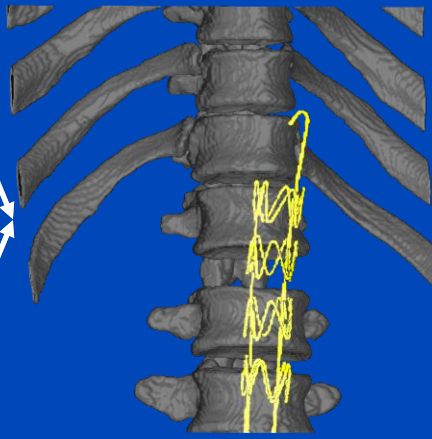
Acquire x-ray projections continuously

Topic of this talk

Compute a 3D reconstruction of the tools with high temporal resolution (~ 5 vps) using the latest few x-ray projections



Slowly update a prior 3D reconstruction of the patient using the latest x-ray projections



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Prior Work on Few-View Tool Reconstruction

Algorithms specializing in the reconstruction of curvilinear structures:

- Reconstruction of single guidewires or catheters from two x-ray projections [1-3], or from a single projection + prior 3D data set [4-5]

More general tool reconstruction algorithms:

- Reconstruction of guidewires and stents from about 16 x-ray projections [6-9]
- Reconstruction of guidewires, stents and coils from only four simultaneous x-ray projections [10]

This work builds on reference [10].

[1] Baert, Niessen et al., *IEEE Trans. Med. Imaging*, Vol. 22, No. 10, pp. 1252–1258, 2003.

[2] Hoffmann, Strobel et al., *MICCAI*, pp. 584–591, 2012.

[3] Wagner, Mistretta et al.,, *Med. Phys.*, Vol. 43, No. 3, pp. 1324–1334, 2016.

[4] Brückner, Denzler et al., *MICCAI*, pp. 386–393, 2009.

[5] Walsum, Niessen et al., *IEEE Trans. Med. Imaging*, Vol. 24, No. 5, pp. 612–623, 2005.

[6] Kuntz, Kachelrieß, Bartling et al., *Phys. Med. Biol.*, Vol. 58, No. 10, pp. 3283–3300, 2013.

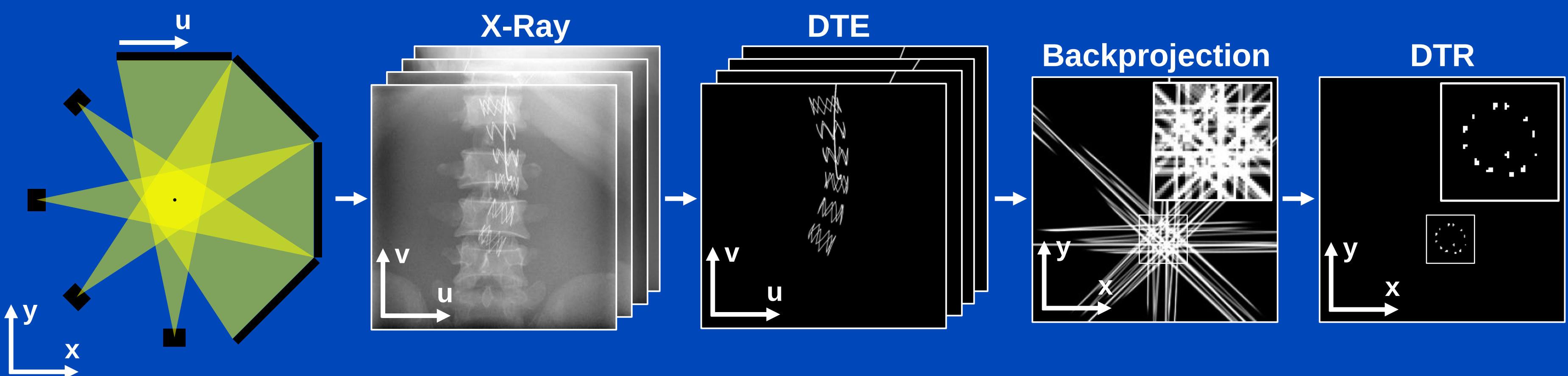
[7] Kuntz, Kachelrieß, Bartling et al., *Eur. Radiol.*, Vol. 23, No. 6, pp. 1669–1677, 2013.

[8] Flach, Kachelrieß et al., *Phys. Med. Biol.*, Vol. 59, No. 24, pp. 7865–7887, 2014.

[9] Flach, Kachelrieß et al., *Med. Phys.*, Vol. 40, No. 10, p. 101909, 2013.

[10] Eulig, Kachelrieß et al., *Med. Phys.*, Vol. 48, No. 10, pp. 5837–5850, 2021.

Prior Work - Tool Reconstruction Pipeline[1]



Acquire four x-rays simultaneously

Apply the deep tool extraction (DTE)

Backproject the DTE output images

Apply the deep tool reconstruction (DTR)

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Congratulations

This paper received the Sylvia&Moses Greenfield Award for the best scientific paper in Medical Physics in 2021.

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[1] Eulig, Kachelrieß et al., *Med. Phys.*, Vol. 48, No. 10, pp. 5837–5850, 2021.

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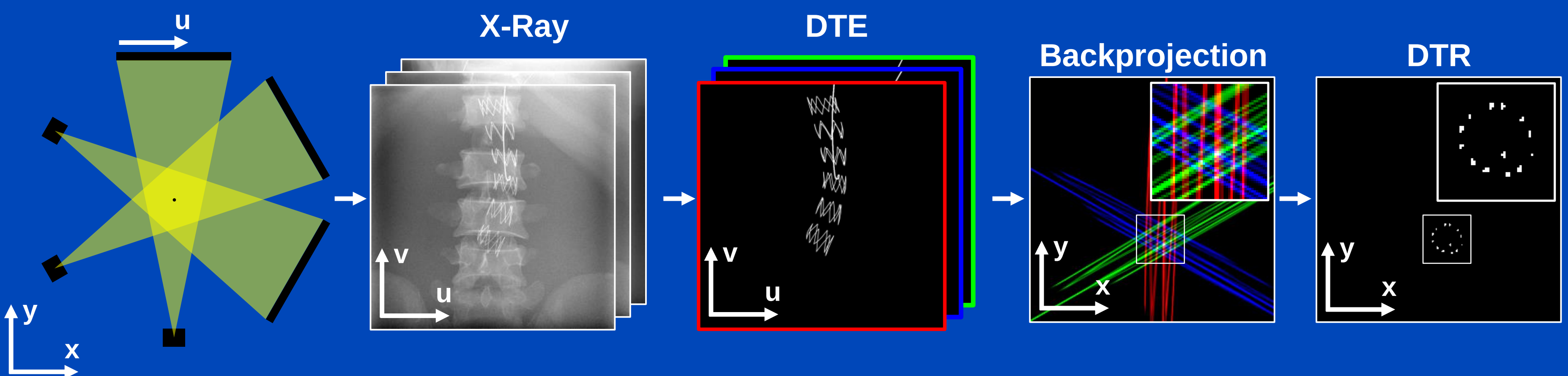
Tool Reconstruction Pipeline



Acquire four x-rays simultaneously

Apply the deep tool extraction (DTE)

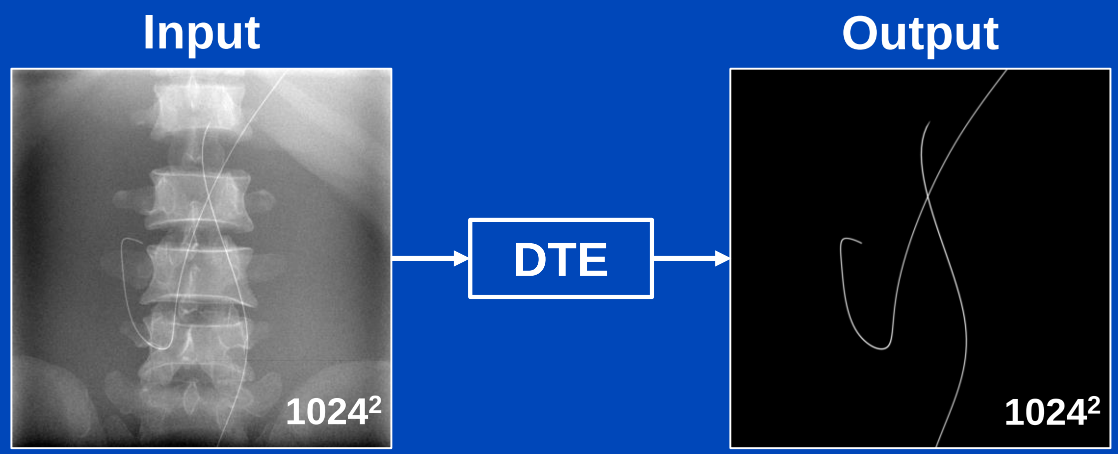
Backproject the DTE output images

Apply the deep tool reconstruction (DTR)

This work:

- Three instead of four simultaneous x-ray projections
- Improved DTR:
  - 3D U-Net instead of a 2.5D U-Net
  - per-projection backprojections (3-channel backprojection) as input

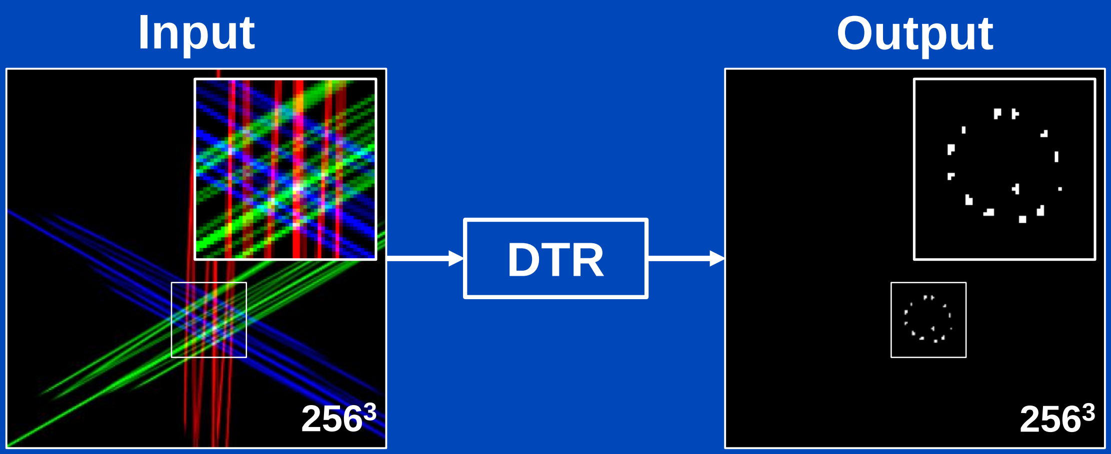
Deep Tool Extraction (DTE)



- Architecture: U-Net-like [1] CNN with 7 stages
- Generation of training & validation data:
  - Combination of CBCT x-ray projections of patients without tools and forward projections of simulated guidewires and stents.
- Dataset:
  - 12,000 forward projections of simulated guidewires and stents
  - 2751 clinical CBCT x-ray projections from nine 3D scans
- Loss: mean absolute error

[1] Ronneberger, Brox et al., *MICCAI*, pp. 234-241, 2015.

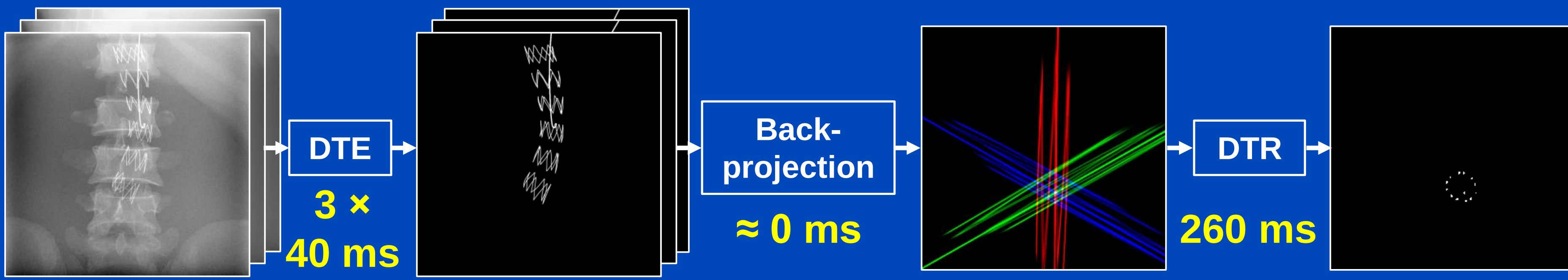
Deep Tool Reconstruction (DTR)



- Architecture: 3D U-Net-like [1] CNN with 6 stages.
- Training & validation data: forward and backprojections of simulated guidewires and stents
- Dataset: 40,000 scenes, each containing one or two guidewires and one stent
- Loss: soft Dice loss with Laplacian smoothing
- Training was performed twice with different input:
  - 1-channel backprojection (all projections backprojected into the same volume)
  - 3-channel backprojection (each projection backprojected into a separate volume)

[1] Cicek, Ronneberger et al., *MICCAI,* 424-432, 2016.

Real Time Capability



- Inference time on an NVIDIA RTX 3090: 380 ms
- 2.6 volumes per second (vps) already possible
- Many possibilities to increase vps: next generation GPU(s), 8-bit quantization, less feature channels, …

Stop Motion Measurements

- Training on simulated data
- Results on stop motion measurements:
  - flat detector
  - For each time step t: 3D scan with fine angular sampling
  - Choose three projections from each 3D scan:

    t = 1: 0°, 60°, 120°

    t = 2: 19°, 79°, 139° ← 19° rotation between time steps to collect projections suitable for update of background patient volume

    …
  - Objects: anthropomorphic trunk phantom + extension + tools placed between phantom and extension
  - Motion: sinusoidal motion of phantom in superior-inferior direction (mimicking cardiac motion) + pulling of guidewire
  - Three scenes, each 8 – 10 time steps long, were captured:
    1. Two guidewires
    2. One stent
    3. Guidewire inside stent
  - 80 kV, 0.80 – 1.15 mAs per projection

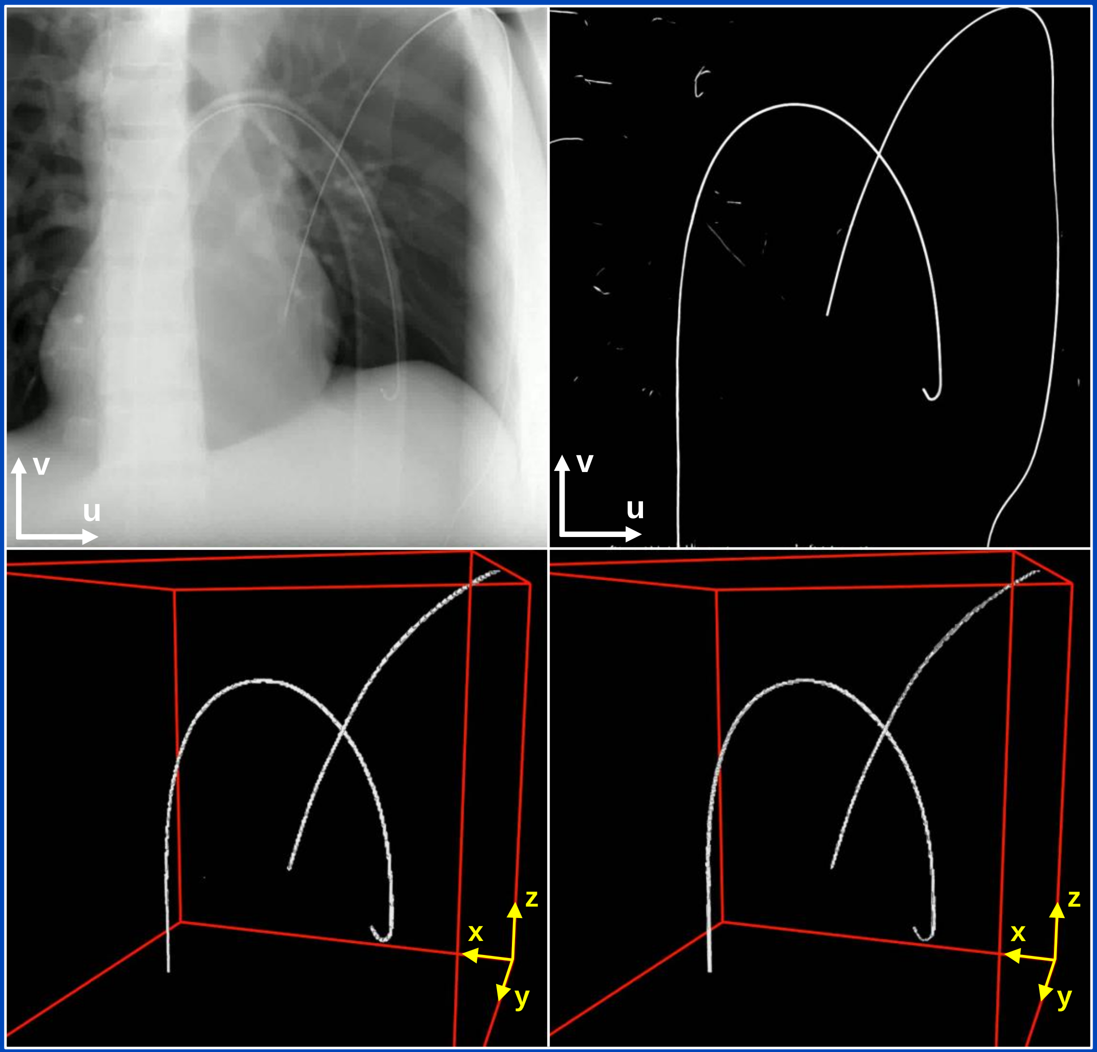
Results - Scene 1

One of the three x-ray projections

DTE Output

DTR Output

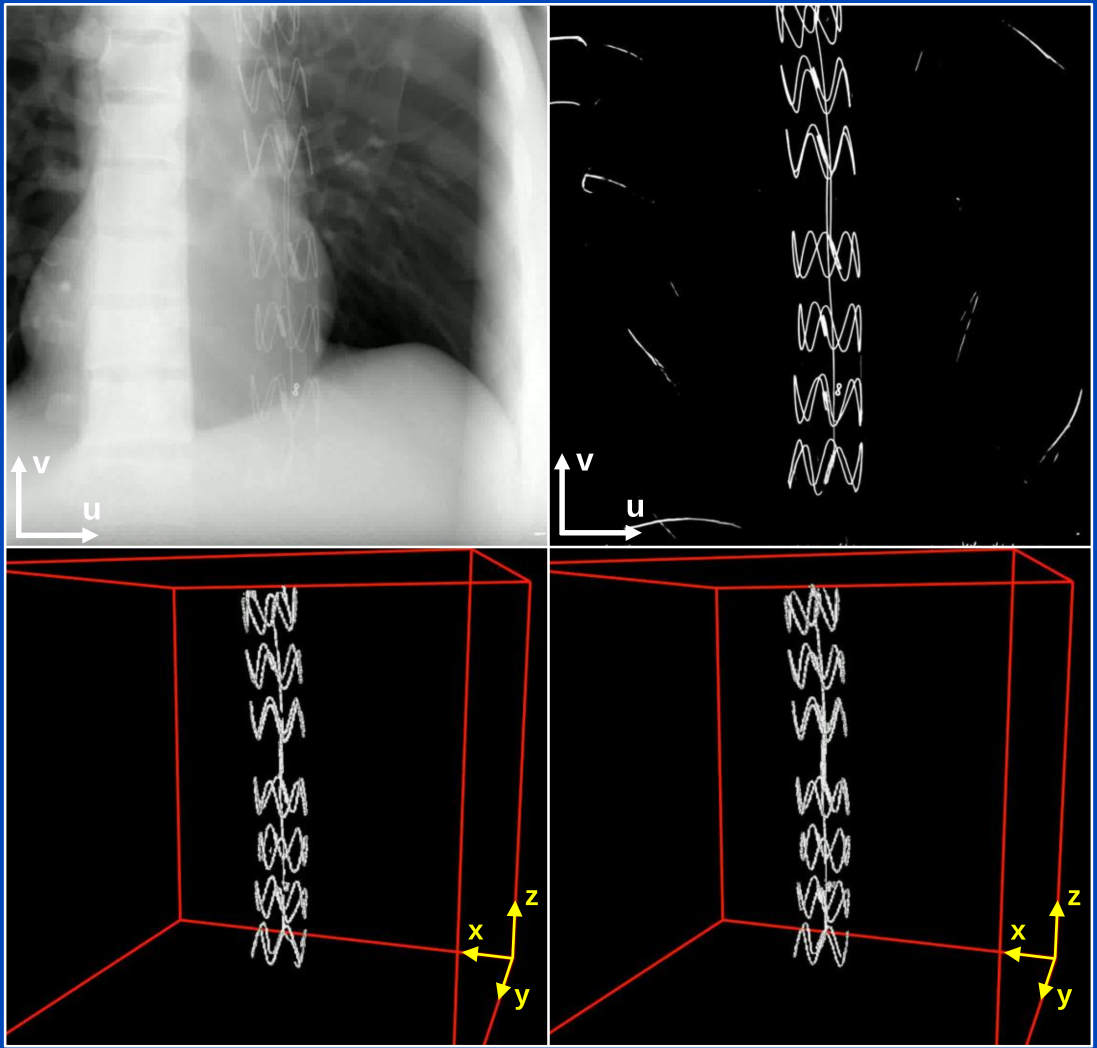
Ground Truth



Results - Scene 2

One of the three x-ray projections

DTE Output



DTR Output

Ground Truth

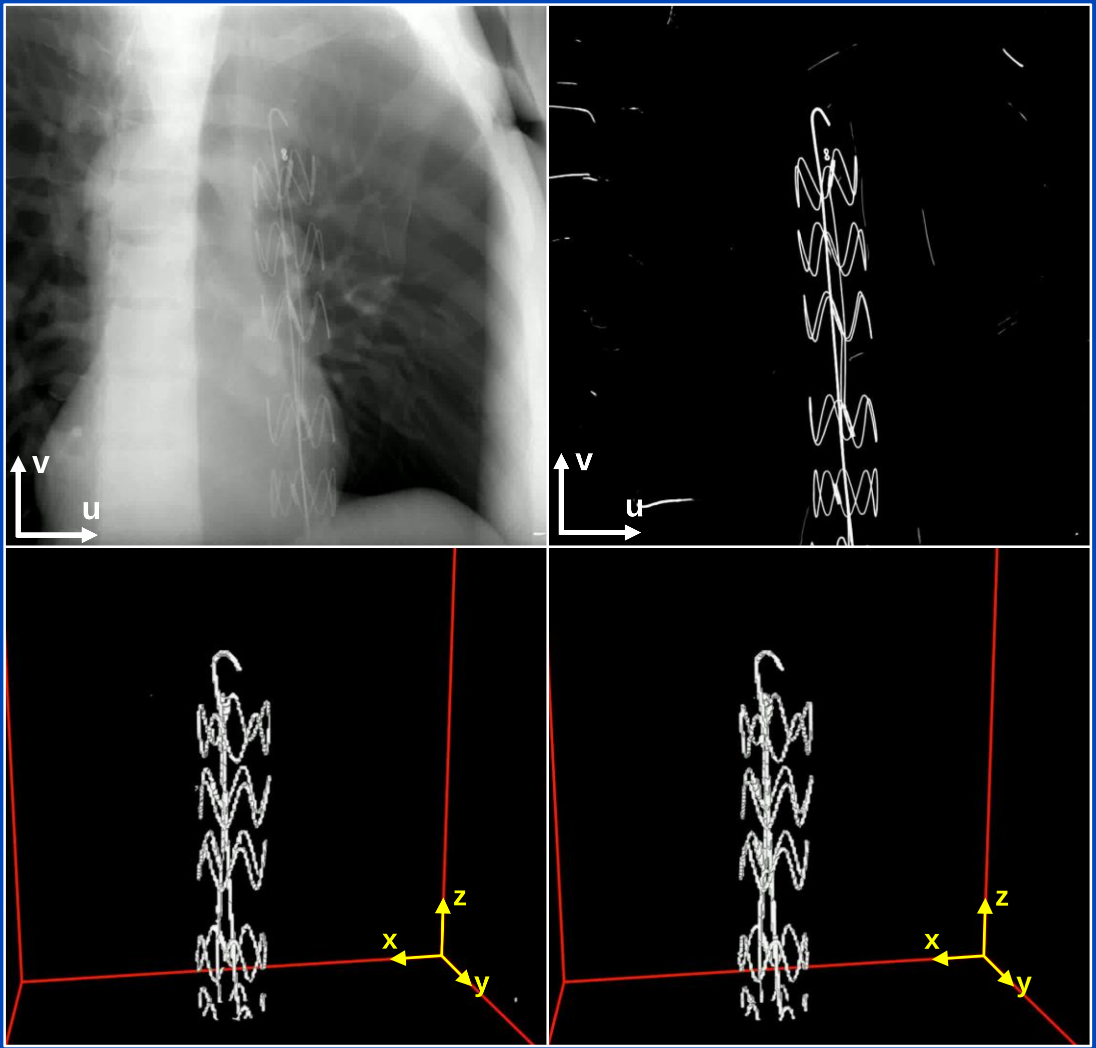
Results - Scene 3

One of the three x-ray projections

DTE Output

DTR Output

Ground Truth



Quantitative Evaluation

- Ground truth 3D reconstruction (GT) is threshold-segmented filtered backprojection
- Diameter of guidewires and struts in GT is uncertain, because it is very sensitive to the threshold
- Therefore, not the Sørensen-Dice coefficient, but a centerline-based metric is used
- Center lines of the ground truth *C*(GT) and the DTR output *C*(Y) computed by the 3D thinning algorithm of Lee et al. [1]
- Figure of merit: $\overline{D}_{C(\mathrm{GT}),C(\mathrm{Y})}$: average distance between the voxels of *C*(GT) and *C*(Y)

Scene	$\overline{D}_{C(\mathrm{GT}),C(\mathrm{Y})}$, 1-channel backproj.	$\overline{D}_{C(\mathrm{GT}),C(\mathrm{Y})}$, 3-channel backproj.
1	0.30 mm	0.26 mm
2	0.33 mm	0.27 mm
3	0.33 mm	0.28 mm

Tab. 1: figures of merit averaged over the time steps of each scene.

[1] Lee, Chu et al., *CVGIP,* Vol. 56, No. 6, pp. 462–478, 1994.

Conclusions and Outlook

- Reconstruction of guidewires and stents from only three x-ray projections
- Submillimeter accuracy demonstrated on measured data of an anthropomorphic phantom
- Close to real-time (380 ms)

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (www.dkfz.de), or directly through Prof. Dr. Marc Kachelrieß (marc.kachelriess@dkfz.de).

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.